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Combination of CDF and DØ Results on the Mass of the Top Quark

The Tevatron Electroweak Working Group[1]
for the CDF and DØ Collaborations

Abstract

We summarize the published top-quark mass measurements from the CDF and DØ experiments at Fermilab. We combine published Run-I (1992-1996) measurements with the most recent published Run-II (2001-present) measurements using up to 340 pb^{-1} of data. Taking correlated uncertainties properly into account the resulting mass of the top quark is $M_{\text{t}} = 174.2 \pm 2.0(\text{stat}) \pm 2.6(\text{syst})$ GeV/c^2, which corresponds to a total uncertainty of 3.3 GeV/c^2, i.e. 1.9% precision.
Since this combination uses only a subset of the available analyses and data sets, it does not supersede our latest world average combination of $M_{\text{t}} = 172.5 \pm 1.3(\text{stat}) \pm 1.9(\text{syst})$ GeV/c^2, which is based on the latest published and preliminary results.

[1]WWW access at `http://tevewwg.fnal.gov`
The members of the TEVEWWG who contributed significantly to the analysis described in this note are:
E. Brubaker (brubakee@fnal.gov), F. Canelli (canelli@fnal.gov), R. Demina (demina@fnal.gov), R. Erbacher (robine@fnal.gov), I. Fleck (fleck@fnal.gov), D. Glenzinski (douglasg@fnal.gov), G. Gutierrez (gaston@fnal.gov), M. W. Grünewald (mwg@fnal.gov), A. Juste (juste@fnal.gov), T. Maruyama (maruyama@fnal.gov), A. Quadt (quadt@fnal.gov), E. Thomson (thomsone@fnal.gov), C. Tully (tully@fnal.gov), E. W. Varnes (varnes@fnal.gov), D. O. Whiteson (danielw@fnal.gov), U.K. Yang (ukyang@fnal.gov).

1 Introduction

The experiments CDF and DØ, taking data at the Tevatron proton-antiproton collider located at the Fermi National Accelerator Laboratory, have made several direct experimental measurements of the top-quark pole mass, $M_{\rm t}$. The pioneering measurements were based on about 100 pb^{-1} of Run-I (1992-1996) data [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12] and include results from the $t\overline{t} \to qq'bqq'\overline{b}$ (all-j), the $t\overline{t} \to \ell\nu qq'b\overline{b}$ (l+j), and the $t\overline{t} \to \ell^+\nu b\ell^-\overline{\nu}\overline{b}$ (di-l) decay channels[2]. Results using approximately 340 pb^{-1} of Run-II (2001-present) data have been recently published in the l+j and di-l channels [13, 14, 15]. More preliminary analyses have been performed in the l+j and di-l channels using $370 - 750$ pb^{-1} of data and improved analysis techniques [16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27].

This note reports the average top quark mass obtained by combining five published Run-I measurements [2, 3, 4, 7, 10, 11] with the most recent published Run-II measurements from CDF [13, 14, 15].[3] Since this combination only uses a subset of the available analyses and data sets, it does not supersede our latest world average combination of $M_{\rm t} = 172.5 \pm 1.3({\rm stat}) \pm 1.9({\rm syst})$ GeV/c^2 [28]. The combination takes into account the statistical and systematic uncertainties and their correlations using the method of references [29, 30]. The most precise individual measurements of $M_{\rm t}$ in this combination are the measurements in the l+j channel from Run I and Run II. These are $173.5^{+3.9}_{-3.8}$ GeV/c^2 (CDF II, [13]) and 180.1 ± 5.3 GeV/c^2 (DØ I, [10]). These have weights in the new $M_{\rm t}$ combination of 57% and 26%, respectively.

The input measurements and error categories used in the combination are detailed in Section 2 and 3, respectively. The correlations used in the combination are discussed in Section 4 and the resulting world average top-quark mass is given in Section 5. A summary and outlook are presented in Section 6.

2 Input Measurements

For this combination seven measurements of $M_{\rm t}$ are used, five published Run-I results and two published Run-II results. The most precise result in each channel is considered for each experiment. In general, the Run-I measurements all have relatively large statistical uncertainties and their systematic uncertainty is dominated by the total jet energy scale (JES) uncertainty. In Run-II both CDF and DØ take advantage of the larger $t\overline{t}$ samples available and employ new analysis techniques to reduce both these uncertainties. In particular the JES is constrained using an in-situ calibration based on the invariant mass of $W \to qq'$ decays in the l+j channel.

[2]Here $\ell = e$ or μ. Decay channels with explicit tau lepton identification are presently under study and are not yet used for measurements of the top-quark mass.

[3]DØ results in the l+j and di-l channels using Run II data are at present close to submission but not yet published and are therefore not included in this combination.

The Run-II CDF analysis in the l+j channel constrains the JES using the in-situ $W \to qq'$ decays. The JES is also determined using "external" calibration samples as was done for the Run-I measurements. This external JES is applied as an additional constraint in this CDF analysis to improve further the total JES uncertainty. Small residual JES uncertainties arising from $\eta-$ and p_T-dependencies and the modeling of b-jets are included in separate error categories. The Run-II CDF measurement in the di-l channel uses only the externally determined JES, some parts of which are correlated with the externally determined Run-I JES as noted below.

The CDF Run-II measurement in the l+j channel requires special treatment in order to account more accurately for the correlations of the JES uncertainties since the fit uses information from both the in-situ and external JES calibrations. In the combination we treat this one measurement as two separate inputs - one which includes only the in-situ JES calibration, $(\text{l+j})_i$, and a second which includes only the JES as determined from the external calibration samples, $(\text{l+j})_e$. We correlate the JES related error categories as described below while taking the rest of the error categories to be 100% correlated between these two inputs. The combination of just these two inputs using these correlations yields the identical central value, statistical, JES, and total systematic uncertainty as the measurement reported in reference [16]. The correlations between these two inputs and the rest of the inputs are as described in Section 4.

The inputs used in the combination are summarized in Table 1 with their uncertainties sub-divided into the categories described in the next Section.

3 Error Categories

We employ the same error categories as used for the previous world average [31]. They have evolved to include a detailed breakdown of the various sources of uncertainty and aim to lump together sources of systematic uncertainty that share the same or similar origin. For example, the "Signal" category discussed below includes the uncertainties from ISR, FSR, and PDF - all of which affect the modeling of the $t\bar{t}$ signal. Additional categories have been added in order to accommodate specific types of correlations. For example, the jet energy scale (JES) uncertainty is sub-divided into several components in order to more accurately accommodate our best estimate of the relevant correlations. Each error category is discussed below.

Statistical: The statistical uncertainty associated with the $M_{\rm t}$ determination.

iJES: That part of the JES uncertainty which originates from in-situ calibration procedures and is uncorrelated among the measurements. In the combination reported here it corresponds to the statistical uncertainty associated with the JES determination using the

	Run-I published					Run-II published		
	CDF			DØ		CDF		
	all-j	l+j	di-l	l+j	di-l	$(\text{l+j})_i$	$(\text{l+j})_e$	di-l
Lumi (pb^{-1})	110	105	110	125	125	320	320	340
Result	186.0	176.1	167.4	180.1	168.4	173.5	173.5	165.2
iJES	0.0	0.0	0.0	0.0	0.0	4.2	0.0	0.0
bJES	0.6	0.6	0.8	0.7	0.7	0.6	0.6	0.5
cJES	3.0	2.7	2.6	2.0	2.0	0.0	2.0	2.2
dJES	0.3	0.7	0.6	0.0	0.0	0.0	0.6	0.8
rJES	4.0	3.4	2.7	2.5	1.1	0.0	2.2	1.1
Signal	1.8	2.6	2.8	1.1	1.8	0.8	0.8	1.3
BG	1.7	1.3	0.3	1.0	1.1	0.5	0.5	0.8
Fit	0.6	0.0	0.7	0.6	1.1	0.6	0.6	1.3
MC	0.8	0.1	0.6	0.0	0.0	0.2	0.2	0.8
UN/MI	0.0	0.0	0.0	1.3	1.3	0.0	0.0	0.0
Syst.	5.7	5.3	4.8	3.9	3.6	4.4	3.3	3.4
Stat.	10.0	5.1	10.3	3.6	12.3	2.7	2.7	6.1
Total	11.5	7.3	11.4	5.3	12.8	5.2	4.3	7.0

Table 1: Summary of the measurements used to determine this average M_{t} using only published M_{t} results. As described in the text, the CDF Run-II measurement in the lepton+jets channel is treated as two inputs in order to more accurately account for the correlations in the jet energy scale uncertainties. All numbers are in GeV/c^2. The error categories and their correlations are described in the text. The total systematic uncertainty and the total uncertainty are obtained by adding the relevant contributions in quadrature.

$W \to qq'$ invariant mass in the CDF Run-II l+j measurement. Residual JES uncertainties, which arise from effects not considered in the in-situ calibration, are included in other categories.

bJES: That part of the JES uncertainty which originates from uncertainties specific to the modeling of b-jets and which is correlated across all measurements. For both CDF and DØ this includes uncertainties arising from variations in the semi-leptonic branching fraction, b-fragmentation modeling, and differences in the color flow between b-jets and light-quark jets. These were determined from Run-II studies but back-propagated to the Run-I measurements, whose rJES uncertainties (see below) were then corrected in order to keep the total JES uncertainty constant.

cJES: That part of the JES uncertainty which originates from modeling uncertainties correlated across all measurements. Specifically it includes the modeling uncertainties associated with light-quark fragmentation and out-of-cone corrections.

dJES: That part of the JES uncertainty which originates from limitations in the calibration data samples used and which is correlated between measurements within the same data-taking period (i.e. Run I or Run II) but not between experiments. For CDF this corresponds to uncertainties associated with the η-dependent JES corrections which are estimated using di-jet data events.

rJES: The remaining part of the JES uncertainty which is correlated between all measurements of the same experiment independent of data-taking period, but is uncorrelated between experiments. This is dominated by uncertainties in the calorimeter response to light-quark jets. For CDF this also includes small uncertainties associated with the multiple interaction and underlying event corrections.

Signal: The systematic uncertainty arising from uncertainties in the modeling of the $t\bar{t}$ signal which is correlated across all measurements. This includes uncertainties from variations in the ISR, FSR, and PDF descriptions used to generate the $t\bar{t}$ Monte Carlo samples that calibrate each method. It also includes small uncertainties associated with biases associated with the identification of b-jets.

Background: The systematic uncertainty arising from uncertainties in modeling the dominant background sources and correlated across all measurements in the same channel. These include uncertainties on the background composition and shape. In particular uncertainties associated with the modeling of the QCD multi-jet background (all-j and l+j), uncertainties associated with the modeling of the Drell-Yan background (di-l), and uncertainties associated with variations of the fragmentation scale used to model W+jets background (all channels) are included.

Fit: The systematic uncertainty arising from any source specific to a particular fit method, including the finite Monte Carlo statistics available to calibrate each method.

Monte Carlo: The systematic uncertainty associated with variations of the physics model used to calibrate the fit methods and correlated across all measurements. For CDF it includes variations observed when substituting PYTHIA [32, 33, 34] (Run I and Run II) or ISAJET [35] (Run I) for HERWIG [36, 37] when modeling the $t\bar{t}$ signal. Similar variations are included for the DØ Run-I measurements.

UN/MI: This is specific to DØ and includes the uncertainty arising from uranium noise in the DØ calorimeter and from the multiple interaction corrections to the JES.

These categories represent the current preliminary understanding of the various sources of uncertainty and their correlations. We expect these to evolve as we continue to probe each

method's sensitivity to the various systematic sources with ever improving precision. Variations in the assignment of uncertainties to the error categories, in the back-propagation of the bJES uncertainties to Run-I measurements, in the approximations made to symmetrize the uncertainties used in the combination, and in the assumed magnitude of the correlations all negligibly effect ($\ll 100$ MeV/c^2) the combined $M_{\rm t}$ and total uncertainty.

4 Correlations

The following correlations are used when making the combination:

- The uncertainties in the Statistical, Fit, and iJES categories are taken to be uncorrelated among the measurements.
- The uncertainties in the dJES category is taken to be 100% correlated among all Run-I and all Run-II measurements on the same experiment, but uncorrelated between Run I and Run II and uncorrelated between the experiments.
- The uncertainties in the rJES and UN/MI categories are taken to be 100% correlated among all measurements on the same experiment.
- The uncertainties in the Background category are taken to be 100% correlated among all measurements in the same channel.
- The uncertainties in the bJES, cJES, Signal, and Generator categories are taken to be 100% correlated among all measurements.

Using the inputs from Table 1 and the correlations specified here, the resulting matrix of total correlation co-efficients is given in Table 2.

The measurements are combined using a program implementing a numerical χ^2 minimization as well as the analytic BLUE method [29, 30]. The two methods used are mathematically equivalent, and are also equivalent to the method used in an older combination [38], and give identical results for the combination. In addition, the BLUE method yields the decomposition of the error on the average in terms of the error categories specified for the input measurements [30].

5 Results

The combined value for the top-quark mass is:

$$M_{\rm t} \;=\; 174.2 \pm 3.3 \text{ GeV}/c^2\,, \tag{1}$$

		Run-I published					Run-II published		
		CDF			DØ		CDF		
		l+j	di-l	all-j	l+j	di-l	$(\text{l+j})_i$	$(\text{l+j})_e$	di-l
CDF-I	l+j	1.00							
CDF-I	di-l	0.29	1.00						
CDF-I	all-j	0.32	0.19	1.00					
DØ-I	l+j	0.26	0.15	0.14	1.00				
DØ-I	di-l	0.11	0.08	0.07	0.16	1.00			
CDF-II	$(\text{l+j})_i$	0.08	0.05	0.03	0.07	0.03	1.00		
CDF-II	$(\text{l+j})_e$	0.51	0.29	0.34	0.26	0.11	0.41	1.00	
CDF-II	di-l	0.26	0.17	0.18	0.17	0.09	0.04	0.30	1.00

Table 2: The resulting matrix of total correlation coefficients used in the top-quark mass combination reported here.

with a χ^2 of 5.8 for 6 degrees of freedom, which corresponds to a probability of 45% indicating good agreement among all the input measurements. The total uncertainty can be sub-divided into the contributions from the various error categories as: Statistical ($\pm$2.0), total JES ($\pm$2.3), Signal ($\pm$1.0), Background ($\pm$0.6), Fit ($\pm$0.4), Monte Carlo ($\pm$0.2), and UN/MI ($\pm$0.4), for a total Systematic ($\pm$2.6), where all numbers are in units of GeV/c^2. The pull and weight for each of the inputs are listed in Table 3. The input measurements and the resulting combined to-quark mass are summarized in Figure 1.

In this combination, for the CDF Run-II l+j measurement using 320 pb^{-1}of data, the in-situ and external JES calibrated inputs each carry approximately the same weight. In the latest world average combination reported Reference [28], the weight of the CDF Run-II l+j input using the in-situ JES calibration carries three times the weight of its counterpart using the external JES calibration. This trend is expected to continue with more data since the in-situ JES uncertainty is expected to improve as the statistics of the $W \to qq'$ sample increase with larger data sets. In contrast the uncertainty on the external JES calibration already has large contributions from modeling uncertainties which may not be reduced with larger data sets.

Although the χ^2 from the combination of all measurements indicates that there is good agreement among them, and no input has an anomalously large pull, it is still interesting to also fit for the top-quark mass in the all-j, l+j, and di-l channels separately. We use the same methodology, inputs, error categories, and correlations as described above, but fit for the three physical observables, $M_{\rm t}^{\rm all-j}$, $M_{\rm t}^{\rm l+j}$, and $M_{\rm t}^{\rm di-l}$. The results of this combination are shown in Table 4 and have χ^2 of 1.4 for 5 degrees of freedom, which corresponds to a probability of 93%.

	Run-I published					Run-II published		
	CDF			DØ		CDF		
	l+j	di-l	all-j	l+j	di-l	$(\text{l+j})_i$	$(\text{l+j})_e$	di-l
Pull	+0.30	−0.62	+1.07	+1.43	−0.46	−0.17	−0.24	−1.45
Weight [%]	1.0	1.1	0.6	26.2	2.8	28.2	28.5	11.6

Table 3: The pull and weight for each of the inputs used to determine this average mass of the top quark.

Parameter	Value (GeV/c^2)	Correlations		
$M_{\text{t}}^{\text{all-j}}$	186.7 ± 11.0	1.00		
$M_{\text{t}}^{\text{l+j}}$	175.6 ± 3.4	0.27	1.00	
$M_{\text{t}}^{\text{di-l}}$	166.1 ± 5.7	0.16	0.35	1.00

Table 4: Summary of the combination of the seven measurements by CDF and DØ in terms of three physical quantities, the mass of the top quark in the all-jets, lepton+jets, and di-lepton channel.

These results differ from a naive combination, where only the measurements in a given channel contribute to the M_{t} determination in that channel, since the combination here fully accounts for all correlations, including those which cross-correlate the different channels.

6 Summary

A combination of published measurements of the mass of the top quark from the Tevatron experiments CDF and DØ is presented. The combination includes five published Run-I measurements and two published Run-II measurements. Taking into account the statistical and systematic uncertainties and their correlations, the average top quark mass result is: $M_{\text{t}} = 174.2 \pm 3.3$ GeV/c^2.

This average of published results has an accuracy of 1.9%, while the present world average top quark mass of $M_{\text{t}} = 172.5 \pm 2.3$ GeV/c^2 [28], which also includes preliminary analyses of more data by CDF and DØ, has an accuracy of 1.3%. Both combinations are limited by the systematic uncertainties, which in turn are dominated by the jet energy scale uncertainty. This systematic is expected to improve as larger data sets are collected since new analysis techniques constrain the jet energy scale using in-situ $W \to qq'$ decays. It can be reasonably expected that with the full Run-II data set the top-quark mass could be known to better than

1%. To reach this level of precision further work is required to determine more accurately the various correlations present, and to understand more precisely the b-jet modeling, Signal, and Background uncertainties which may limit the sensitivity at larger data sets. Limitations of the Monte Carlo generators used to calibrate each fit method may also become important as the precision reaches the 1% level and will warrant further study in the future.

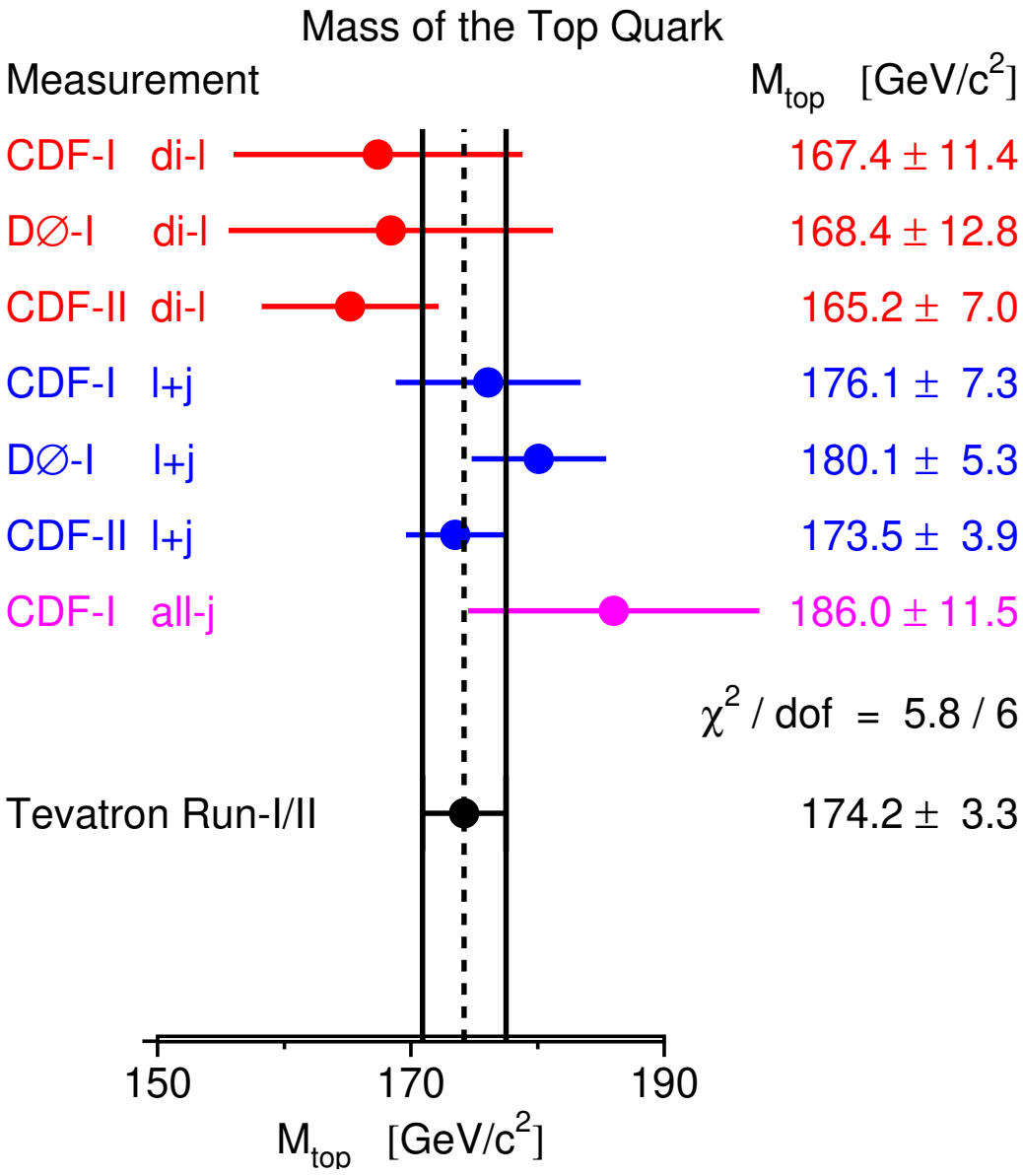

Figure 1: A summary of the input measurements and the resulting combined top-quark mass.

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